EXPERIENCE FROM LARIAT

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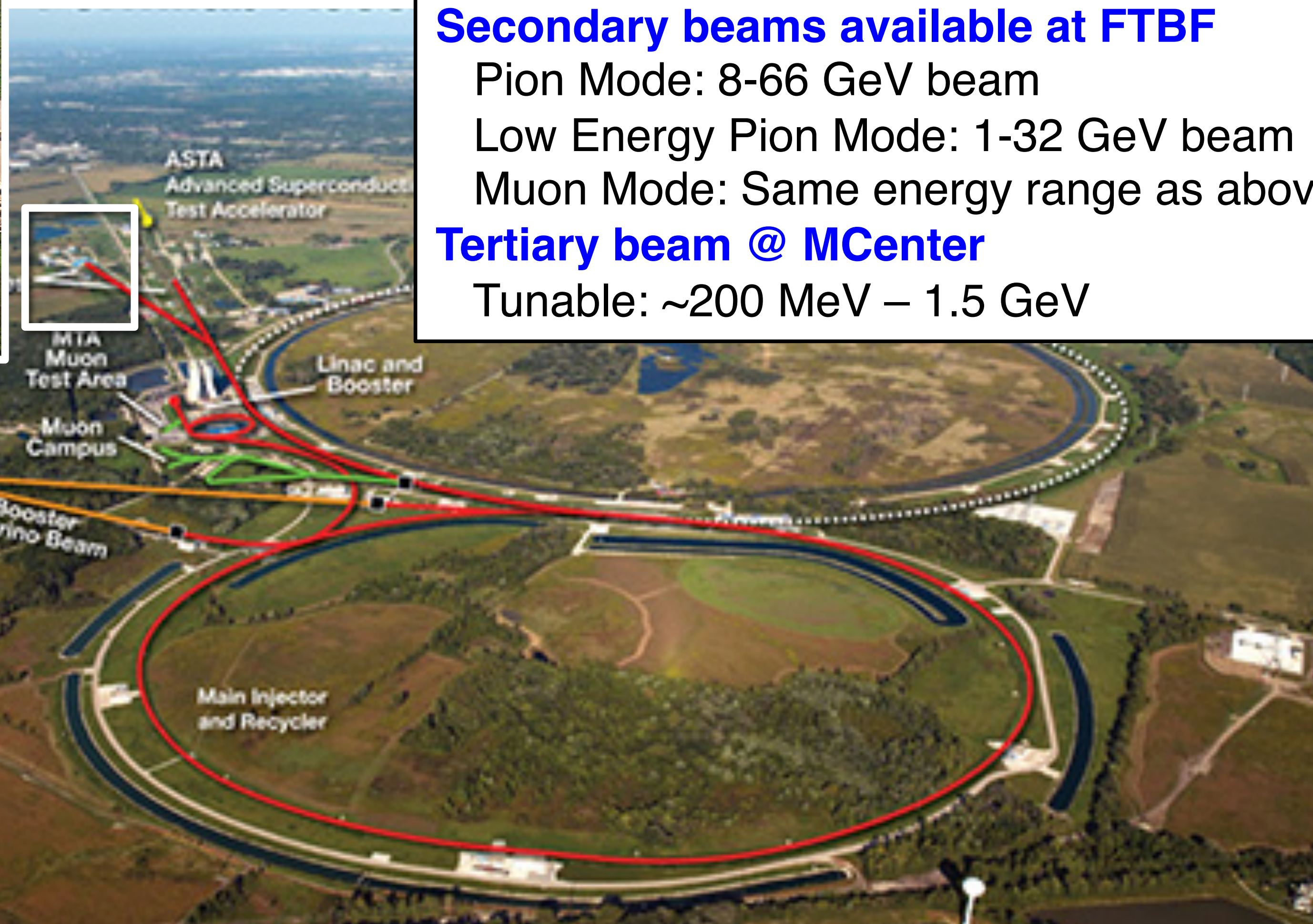
(with many thanks to E. Gramellini and G. Pulliam for much of the content in these slides)

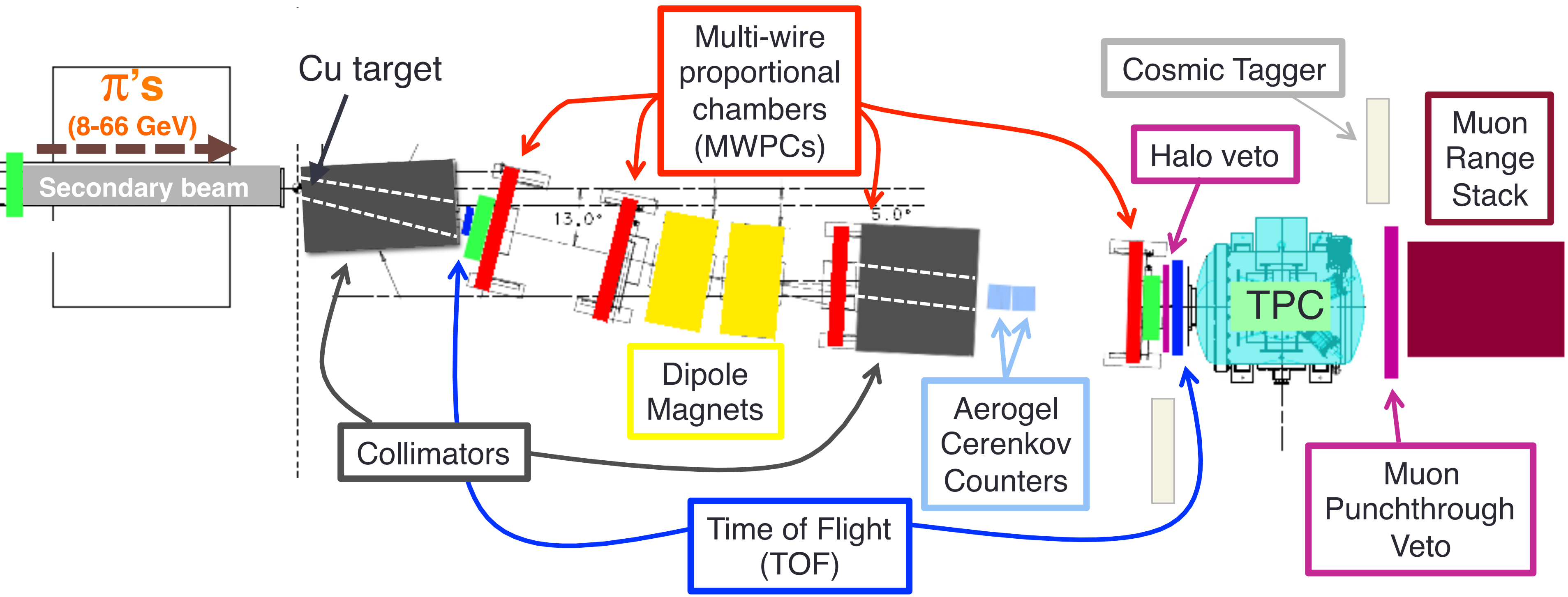
Jan. 27, 2019

Fermilab Test Beam Facility

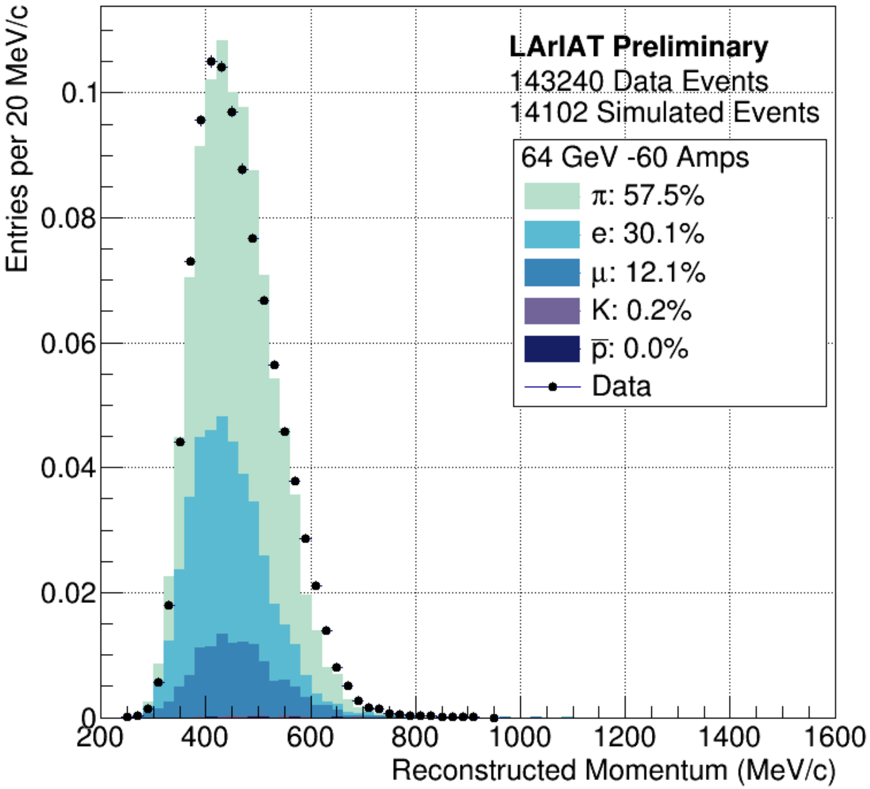


Primary beam
Protons: 120 GeV
Secondary beams available at FTBF
Pion Mode: 8-66 GeV beam
Low Energy Pion Mode: 1-32 GeV beam
Muon Mode: Same energy range as above
Tertiary beam @ MCenter
Tunable: ~200 MeV – 1.5 GeV

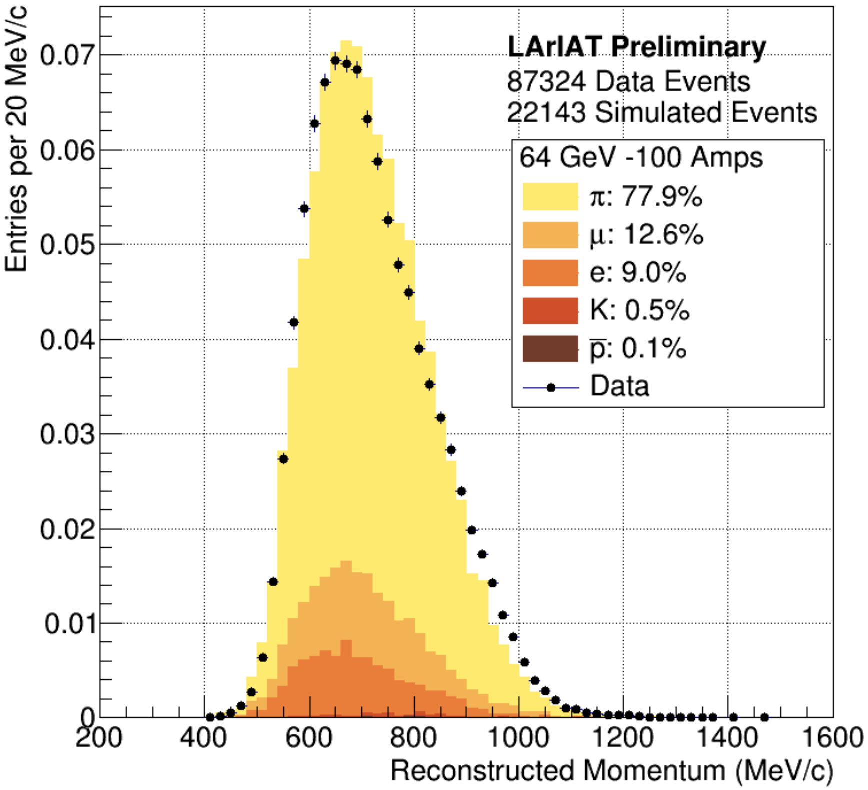
FTBF MCenter Tertiary Beam



Tertiary beam spectra & composition



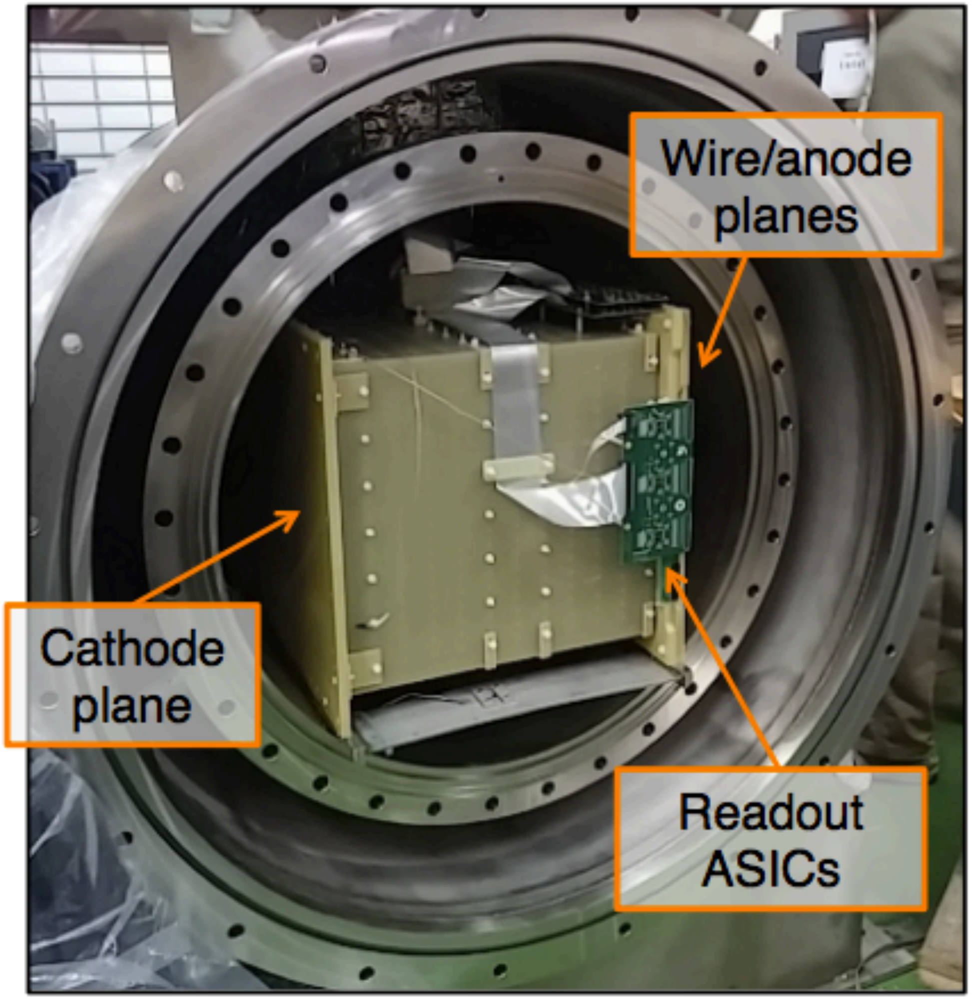
"Low energy tune"



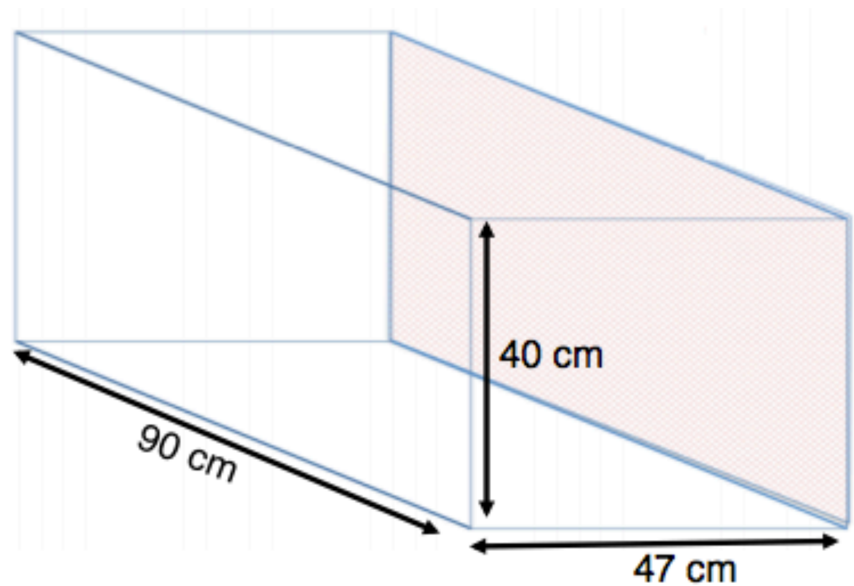
"High energy tune"

- Only negative polarity data shown here
- Beam composition *before* any analysis cuts

LArIAT Experimental Details



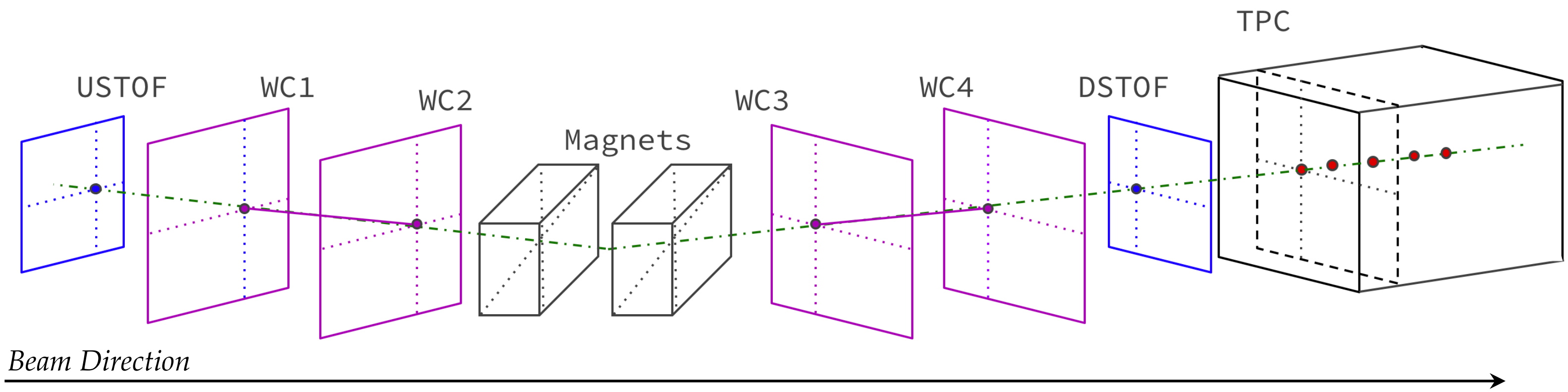
- Time Projection Chamber
  - Repurposed from ArgoNeuT
  - New wireplanes and cold readout electronics (MicroBooNE ASICs)
    - 1 (non-instrumented shield plane: 225 vertical wires
    - 2 readout planes: 240 wires each, ±60º, 4mm pitch (for the analysis discussed here today)
  - Drift field ~500 V/cm (nominal)

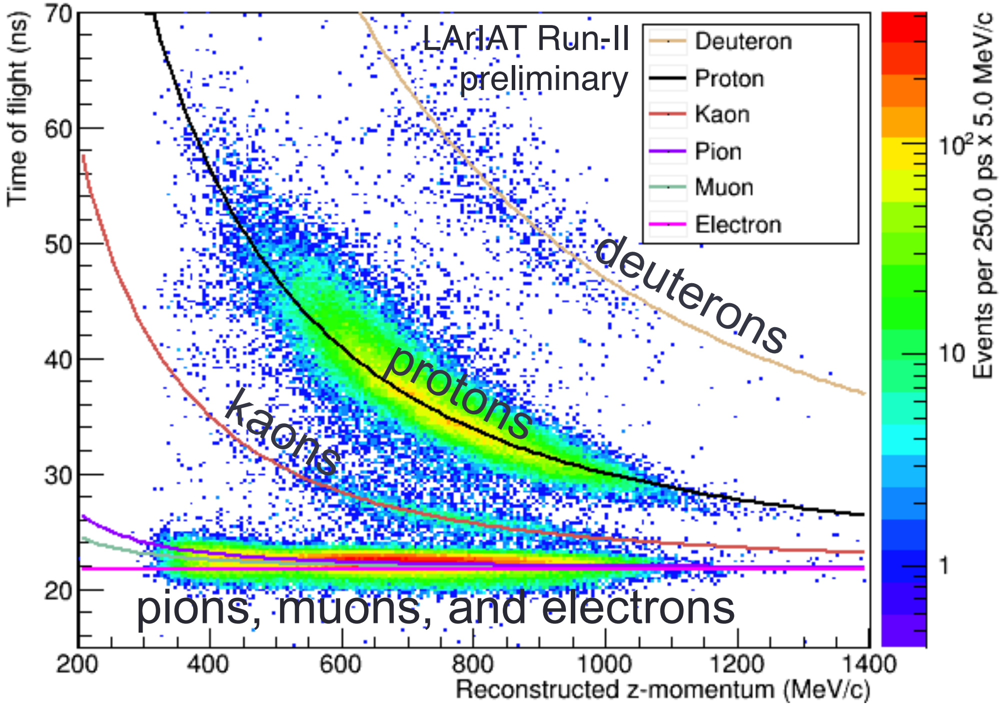


Cross section analysis steps

- Select desired particles using beamline instrumentation
- Match beamline trajectory with track inside TPC
- Divide the TPC into many “thin targets”
  - Each thin target is a binary “experiment”: did the particle interact in this thin target – yes or no? What was its energy at this target?
  - Every TPC track undergoes *many experiments* (one experiment per thin target it travels through).
- Correct for backgrounds and reconstruction effects/ inefficiencies

First, use beamline to select particles of interest





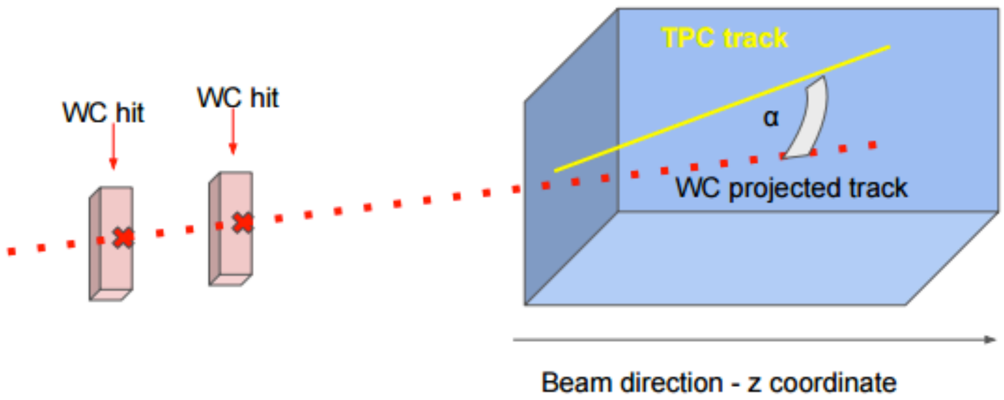
- Magnet polarity can be changed to select either positive or negative particles
- Use wire chambers + magnets to determine momentum
- TOF + magnetic spectrometer enables some distinction among particle types

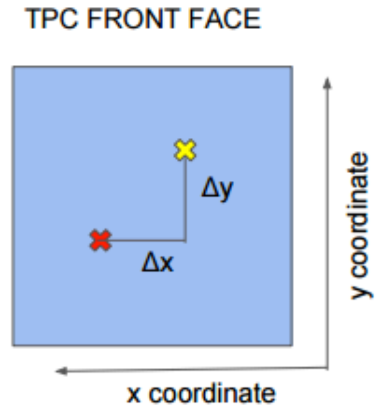
  NB: We cannot distinguish among the light particles (pions, muons, electrons)

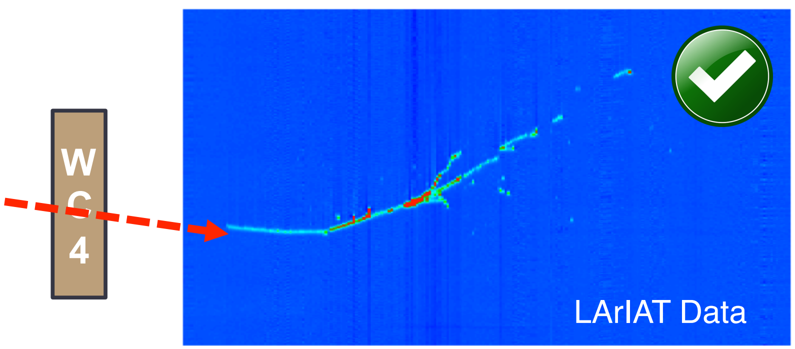
Beamline Momentum Uncertainty

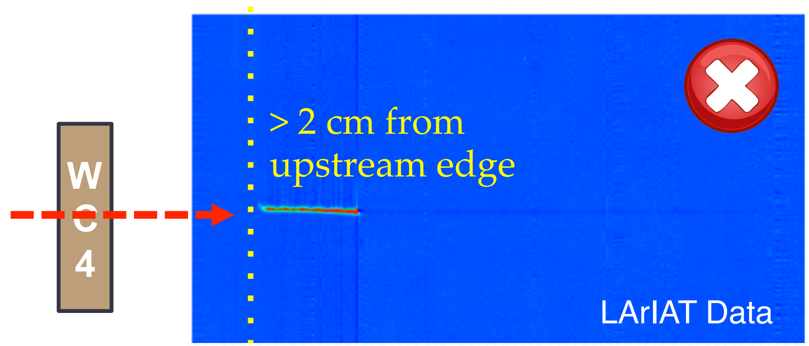
- For the negative pion analysis we currently take 2% as the momentum uncertainty, based on studies done by MINERvA test beam effort (same beamline)
- A study using TOF and known particles (kaons & protons) gives consistent estimate of momentum uncertainty (~2%), but also shows a ~3% shift
- A TPC-range-based cross check of the beamline momentum is in progress
  - Using stopping particles in TPC, determine momentum based on range, extrapolate back to WC4
  - Compare spectrometer momentum measurement with range-based measurement

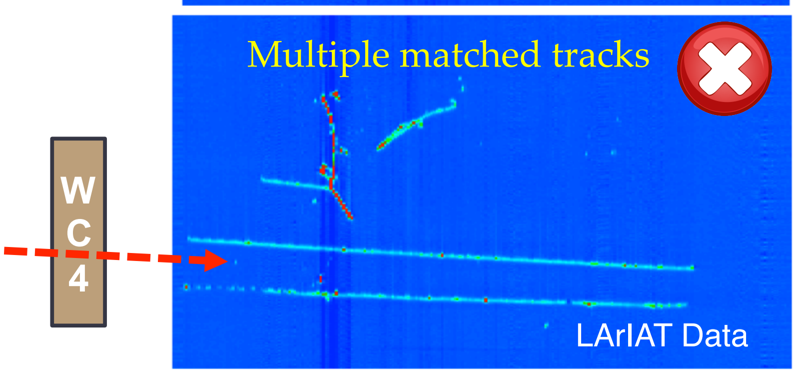
Match beamline track with TPC track

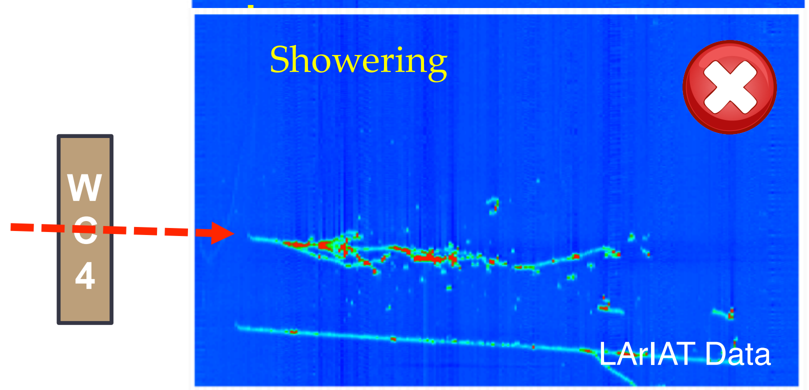




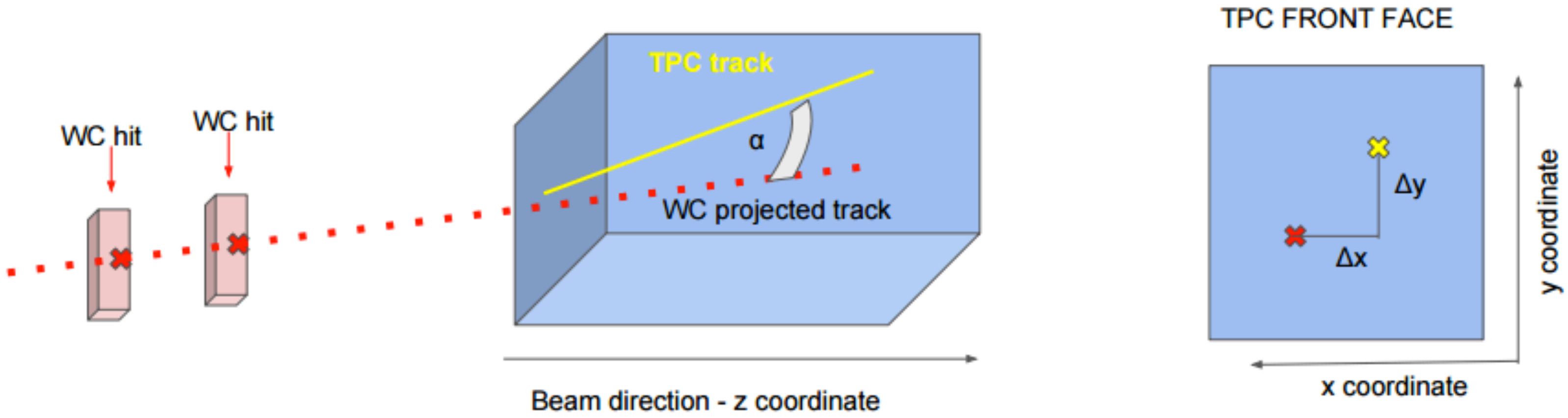








Match beamline track with TPC track



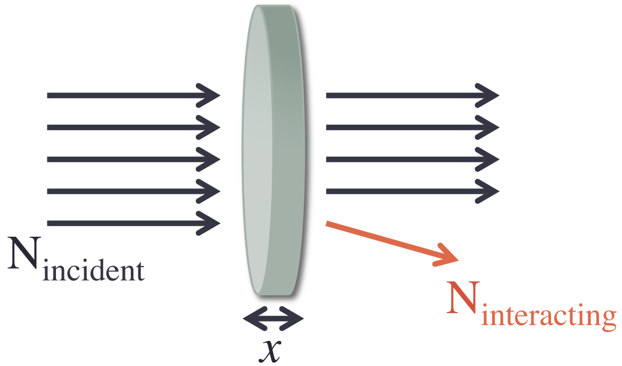
	Run-II Neg Pol	Run-II Pos Pol
1. Events Reconstructed in Beamline	158396	260810
2. Events with Plausible Trajectory	147468	240954
3. Beamline $\pi^-/\mu^-/e^-$ Candidate	138481	N.A.
4. Beamline K^+ Candidate	N.A	2837
5. Events Surviving Pile Up Filter	108929	2389
6. Events with WC2TPC Match	41757	1081
7. Events Surviving Shower Filter	40841	N.A.
8. Available Events For Cross Section	40841	1081

"Thin-Target" Cross Section

- The survival probability of a pion traveling through a thin slab of material is given by:

$$P_{survival} = e^{-\sigma \rho dx}$$

$$\sigma = \text{total interaction cross section}$$
$$dx = \text{thickness of target}$$
$$\rho = \text{density of target material}$$



- We can measure directly the interaction probability as the ratio of the number of interacting pions to incident pions:

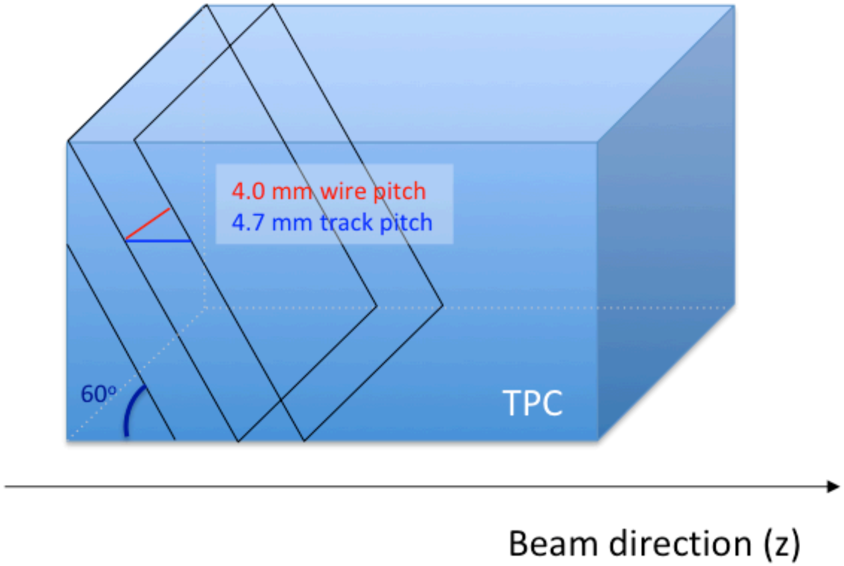
$$\frac{N_{interacting}}{N_{incident}} = P_{interaction} = 1 - P_{survival} = 1 - e^{-\sigma \rho dx}$$

"Thin-Target" Cross Section

- In the limit of a thin target, the interaction probability can be Taylor expanded to solve for the cross section…

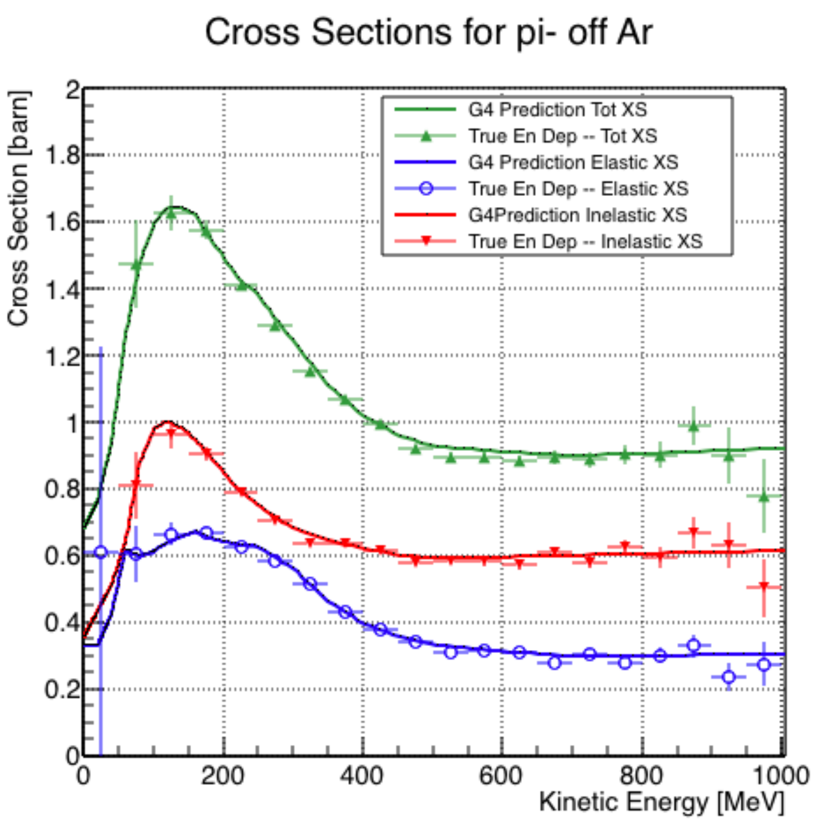
$$P_{interaction} = 1 - e^{-\sigma \rho dx} \simeq 1 - (1 - \sigma \rho dx + O(dx^2))$$

$$\sigma \simeq \frac{1}{\rho dx} P_{interaction} = \frac{1}{\rho dx} \frac{N_{interacting}}{N_{incident}}$$



We can treat TPC wire-to-wire spacing as a series of "thin targets" because we know the energy of the pion as it is incident on each slice.

Proof of Principle

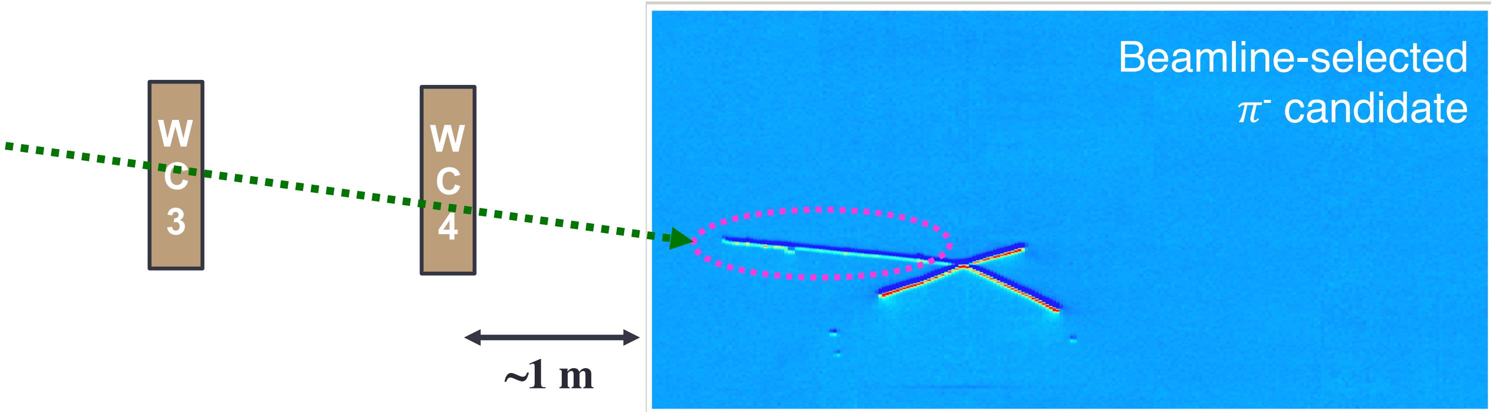


- Using MC truth-level quantities (no reconstruction), divide TPC into slices defined by wire pitch
- In each slice, measure the energy of the particle track and check if it interacted
- Construct the cross section, binned by energy of the particle at each slice

$$\sigma(E_i) \simeq \frac{1}{\rho dx} \frac{N_{interacting}(E_i)}{N_{incident}(E_i)}$$

- The method reproduces the Geant4 predicted cross section

Calculate the initial KE of the particle

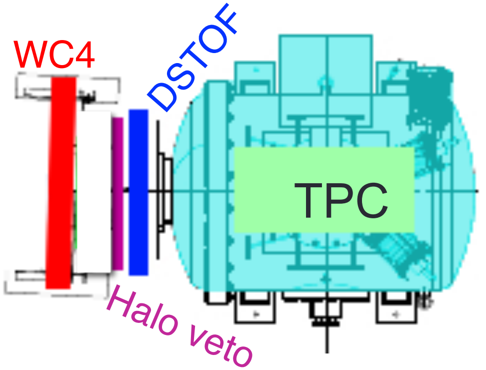


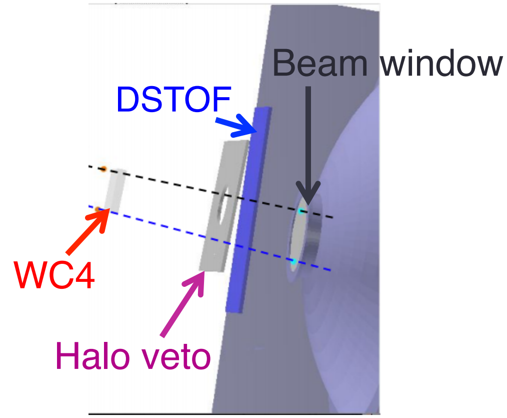
- Use the momentum measured by the beamline magnetic spectrometer to calculate the initial kinetic energy of the candidate (assuming pion mass for this analysis)

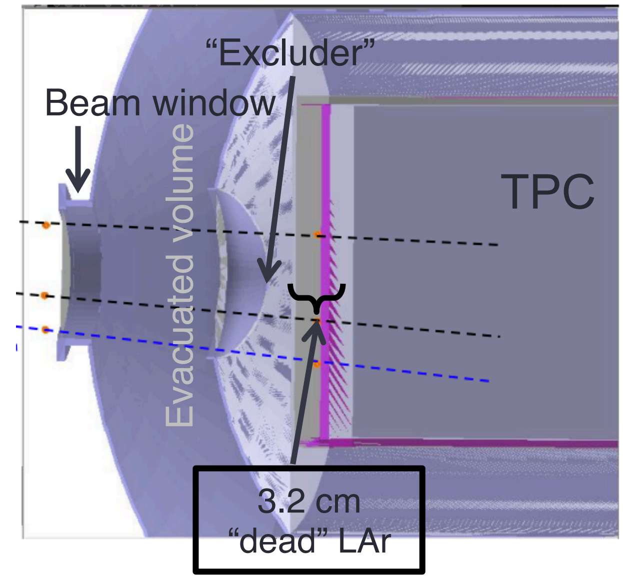
$$\mathrm{KE}_{\mathrm{front\ face}} = \sqrt{p_{beam}^2 + m_\pi^2} - m_\pi - \mathrm{KE}_{\mathrm{loss}}$$

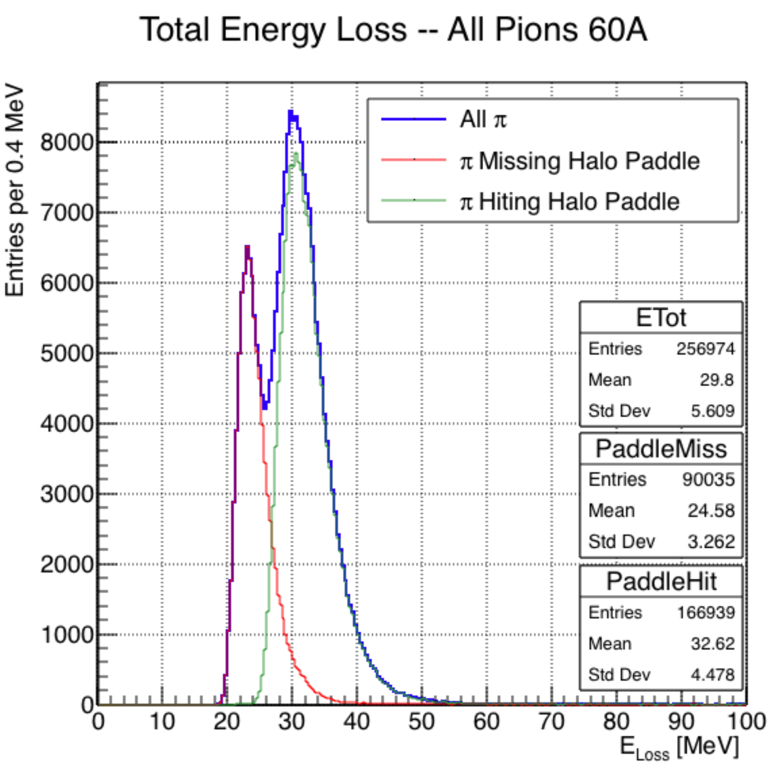
$\mathrm{KE}_{\mathrm{loss}}$ is the amount of energy lost in traveling from WC4 to the start of the TPC active volume.

Energy lost between WC4 and TPC









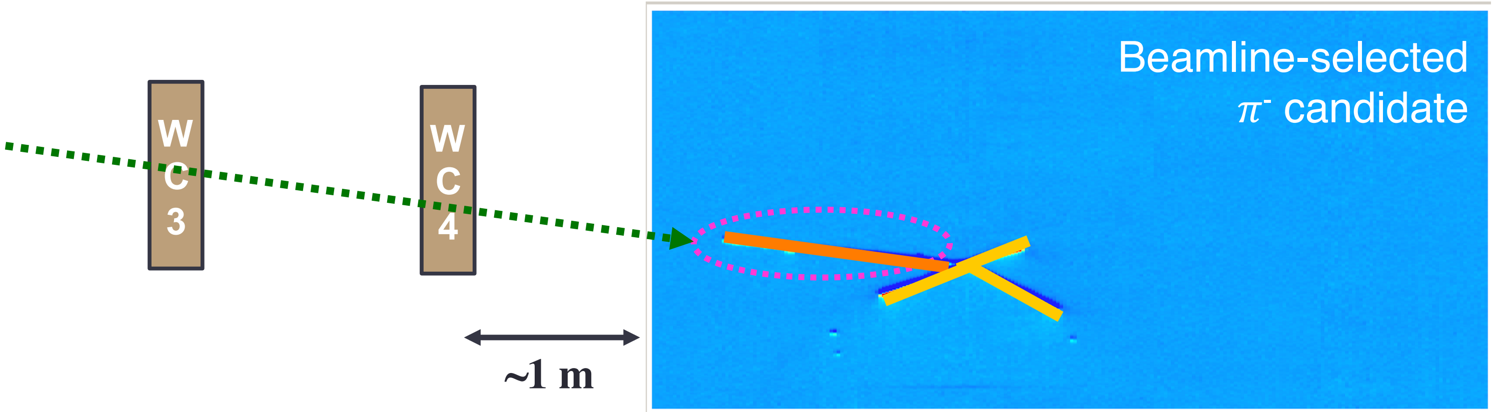
Energy loss depends on particle trajectory

- If it goes through the hole of the halo veto, use flat 25 MeV E_{loss}
- If it goes through the scintillator of the halo veto instead, use flat 33 MeV E_{loss}

Uncertainty on the energy loss is conservatively taken to be the standard deviation of the full distribution (~6 MeV)

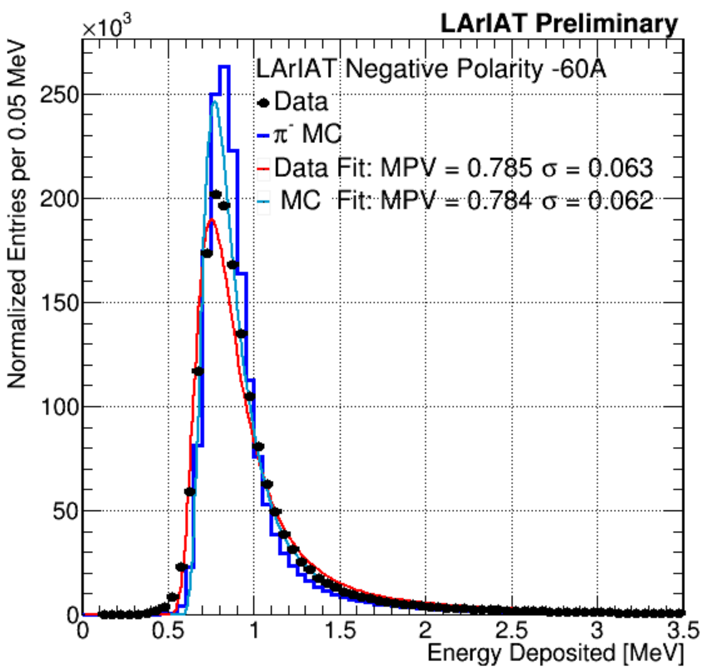
$$\mathrm{KE}_{\mathrm{front\ face}} = \sqrt{p_{beam}^2 + m_\pi^2} - m_\pi - \mathrm{KE}_{\mathrm{loss}}$$

Calculate KE of the particle at each slice

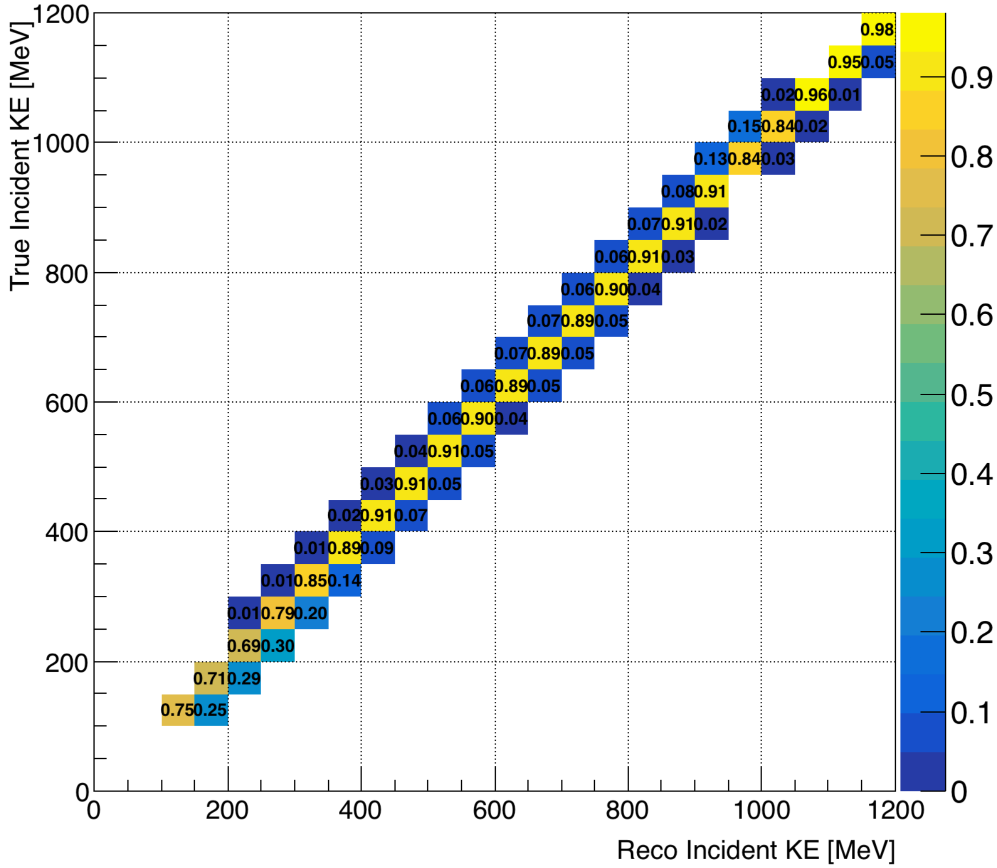


- The KE of the particle at each slice (spacepoint), j, of the TPC track is calculated by:

$$\mathrm{KE}_j = \mathrm{KE}_{\mathrm{front\ face}} - \sum_{i=0}^{j-1} \frac{dE}{dx}\mathrm{dx}_i$$



True vs. Reco Energy

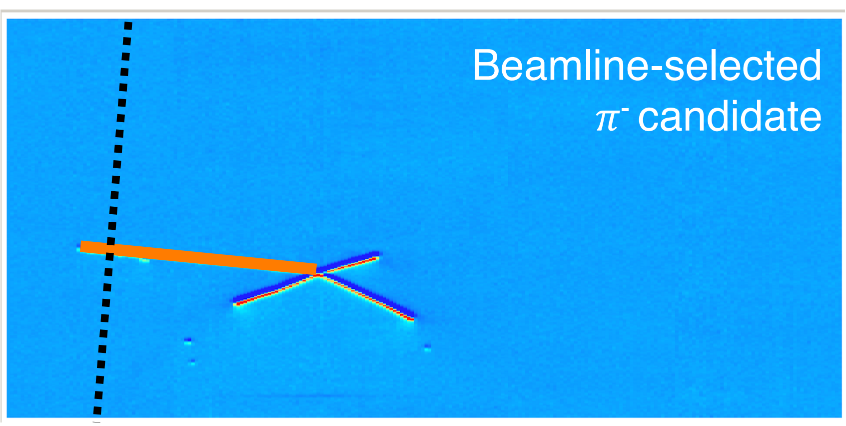


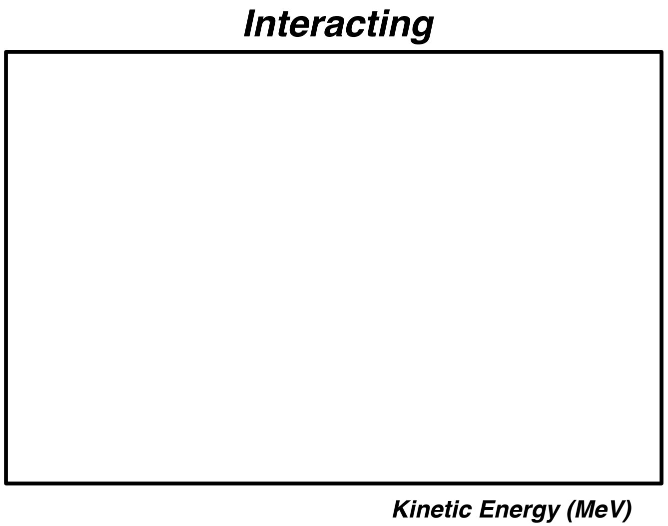
- At each slice, compare true and reco KE
  - Highly diagonal → most of the time we put the particle into the right energy bin
- In a future iteration of the analysis, we could improve by doing some energy unsmearing
  - For this analysis, we did not unsmear

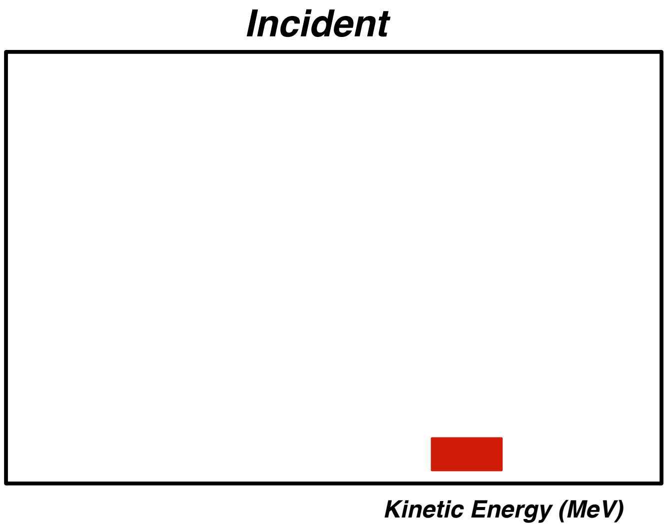
Follow the TPC track, slice by slice

- The slice represents the distance between each 3D spacepoint in the track
- Each slice is an *independent experiment*
- For each slice, ask "Is this the end of the track?"
  - NO: Calculate the kinetic energy of the track at this slice. Add an entry in the "incident" histogram in that KE bin

$$\mathrm{KE}_j = \mathrm{KE}_{\text{front face}} - \sum_{i=0}^{j-1} \frac{dE}{dx} \mathrm{dx}_i$$







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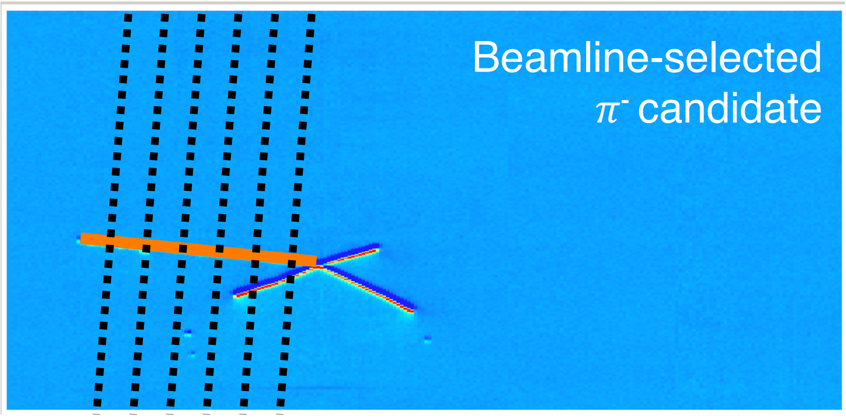
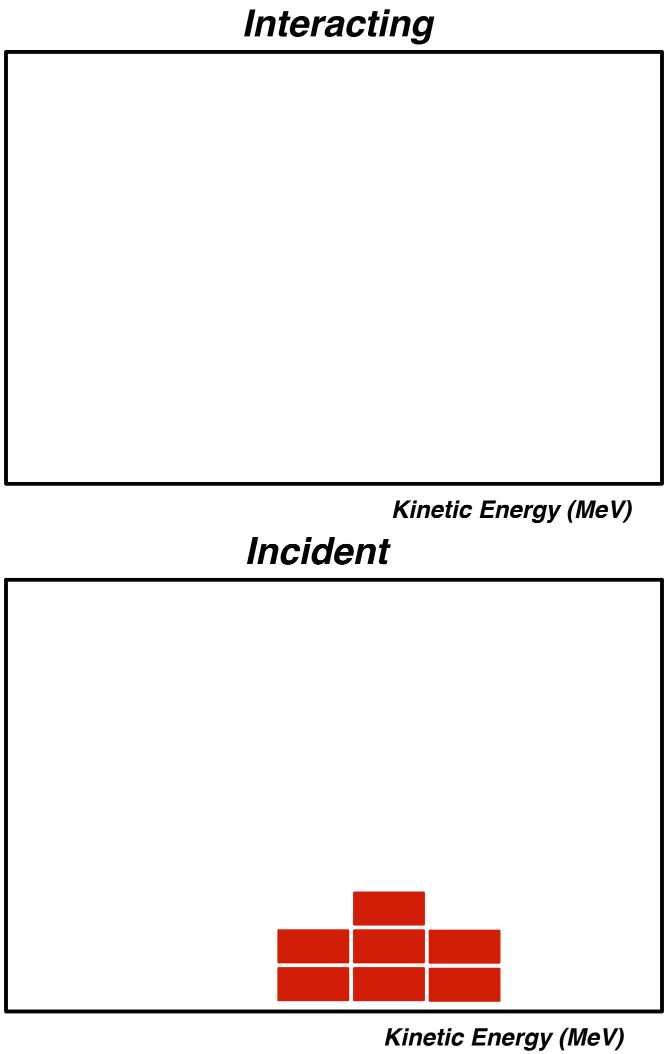
$$\mathrm{KE}_j = \mathrm{KE}_{\text{front face}} - \sum_{i=0}^{j-1} \frac{dE}{dx} \mathrm{dx}_i$$

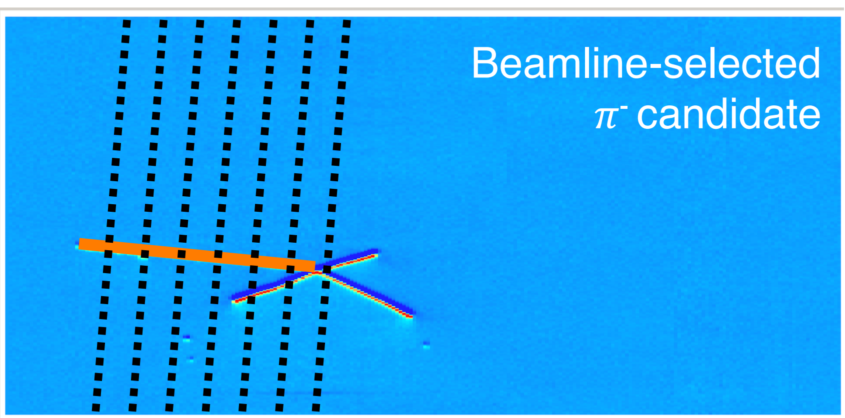




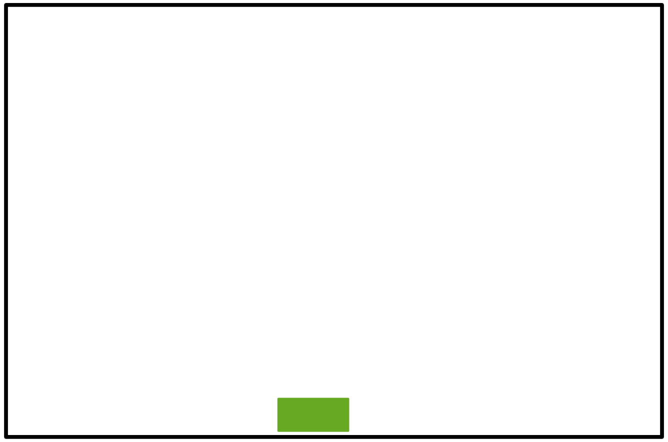
Follow the TPC track, slice by slice

- The slice represents the distance between each 3D spacepoint in the track
- Each slice is an *independent experiment*
- For each slice, ask "Is this the end of the track?"
  - YES!: Calculate the kinetic energy of the track at this slice. Add an entry in both the "interacting" and "incident" histograms

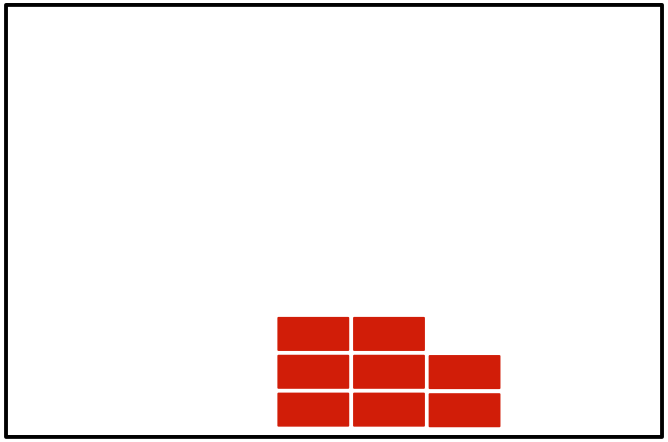
$$\mathrm{KE}_j = \mathrm{KE}_{\mathrm{front\ face}} - \sum_{i=0}^{j-1} \frac{dE}{dx} \mathrm{dx}_i$$



Interacting

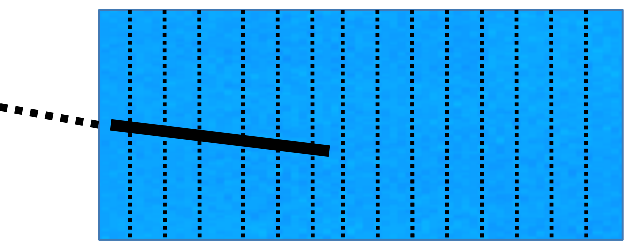


Incident

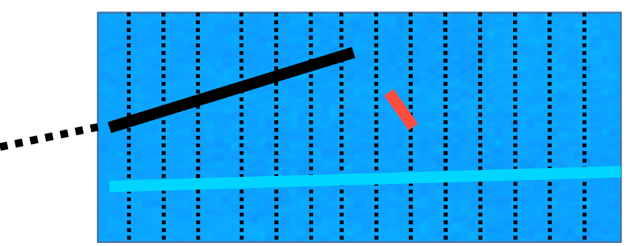


Repeat the same process for all tracks

- Using only WC-to-TPC matched tracks, repeat the process, filling the incident and interacting histograms
  - Ignore other non-matched activity in TPC

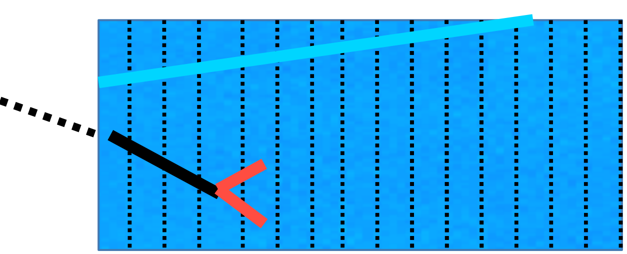


✔ The black track is followed



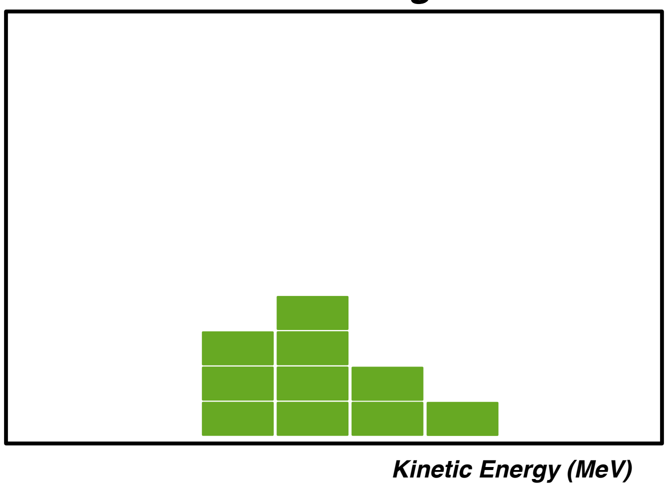
✖ The light blue track is not matched to WC

✖ The red stub is ignored

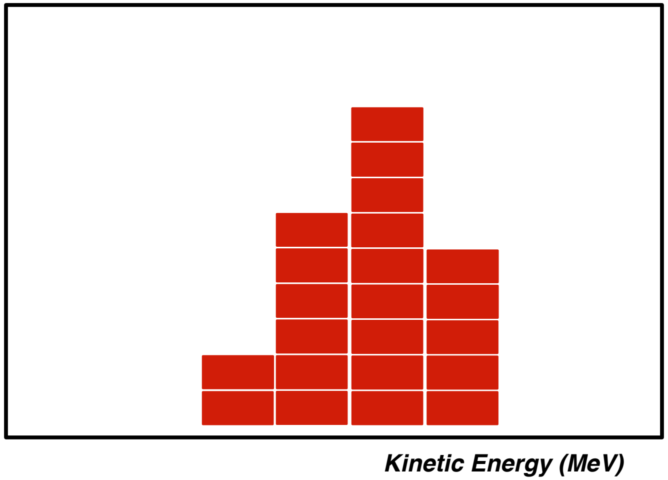


✖ The red tracks do not belong to the original track

Interacting



Incident



Uncorrected Cross Section

- In a perfect experiment (no backgrounds, no reconstruction inefficiencies), the cross section is simply

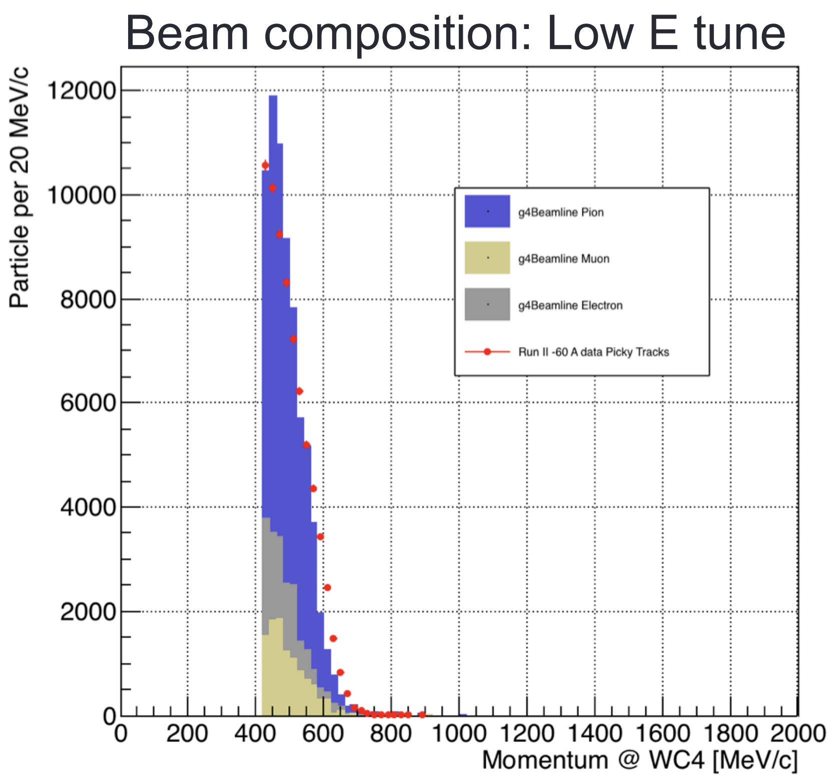
$$\sigma(E_i) \simeq \frac{1}{\rho dx} \frac{N_{interacting}(E_i)}{N_{incident}(E_i)}$$

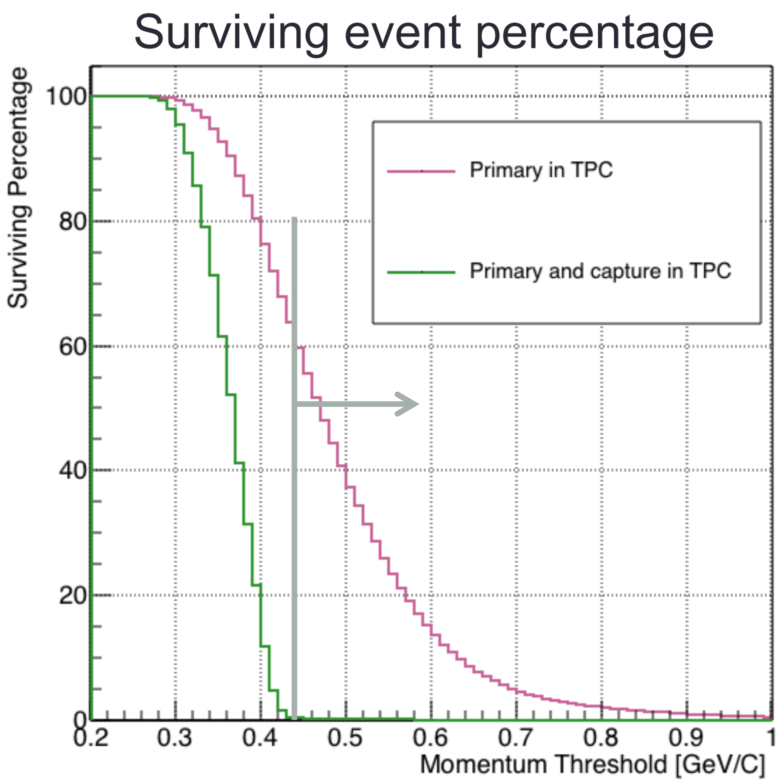
- In real life, we need to subtract background events and correct for reconstruction inefficiencies

$$\sigma(E_i) \simeq \frac{1}{\rho dx} \left(\frac{N_{int}(E_i) - B_{int}(E_i)}{N_{inc}(E_i) - B_{inc}(E_i)} \right) \frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

Removing Intrinsic Backgrounds

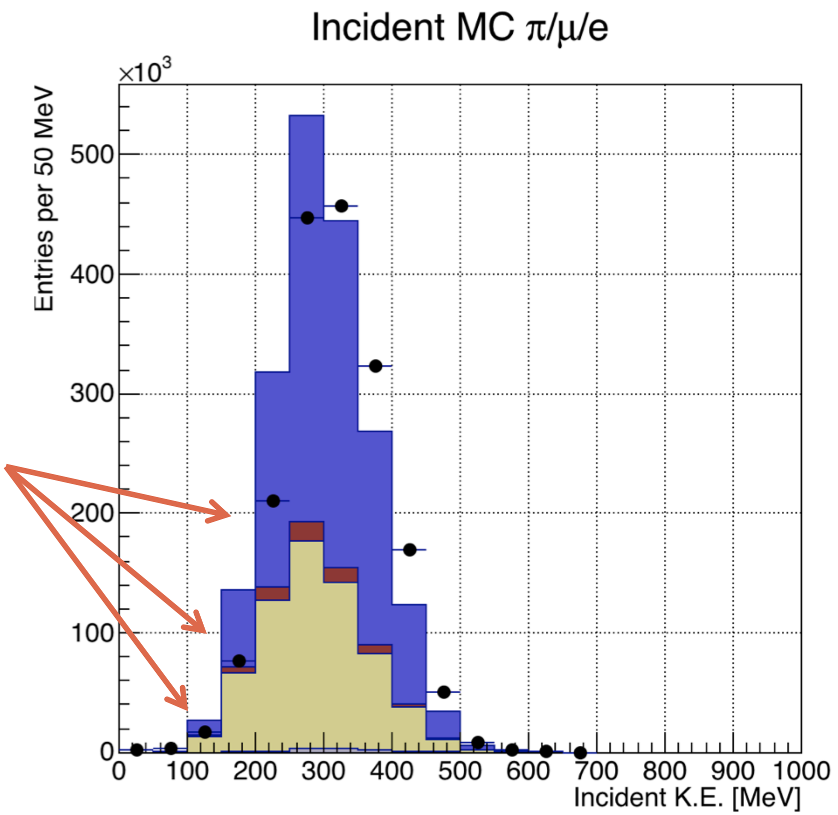
- Pion capture and decay occur mostly at rest
  - Remove most of these by requiring incoming particle to have momentum > 420 MeV/c at final wire chamber before entering TPC





Non-pion beam background subtraction

- Ideally, the MC and data have overall good agreement in the interacting and incident KE distributions
  - Then direct subtraction of background in each bin is straightforward
- In the case of LArIAT's first analysis, our MC shape did not match the data shape very well, leading to unphysical results in some bins if a direct subtraction was done
  - In this circumstance, we chose to use the MC prediction of background in each bin as a *fraction of the total MC bin content*, then the background "subtraction" became a multiplicative correction instead
- Our new MC much better matches the data, and so we should be able to move to the direct background subtraction method for the next iteration of this analysis

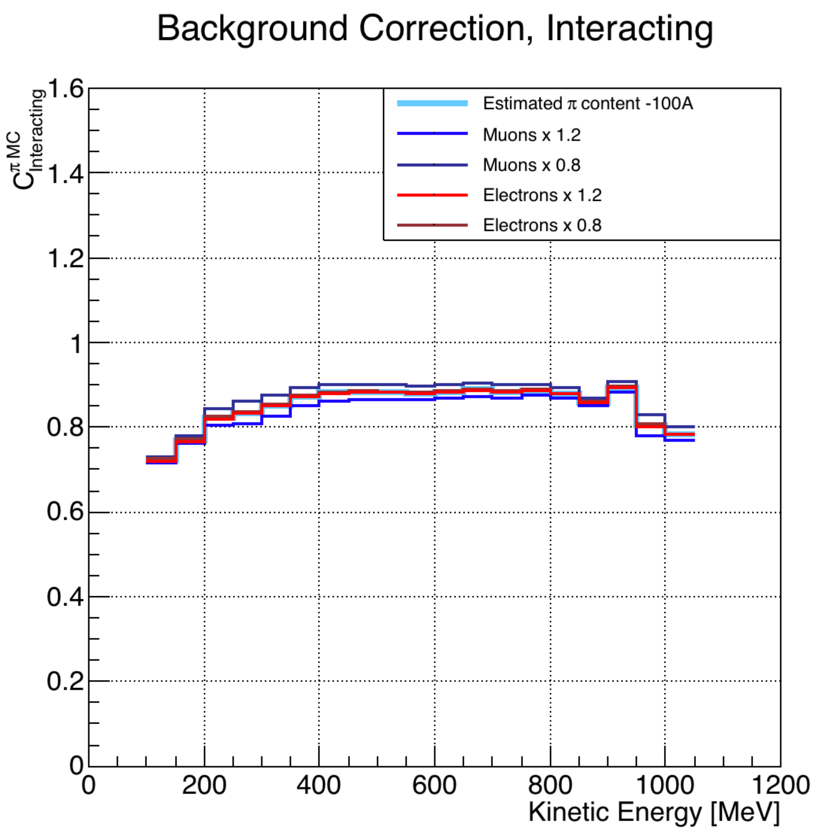


$$\sigma(E_i) \simeq \frac{1}{\rho dx}\left(\frac{N_{int}(E_i) - B_{int}(E_i)}{N_{inc}(E_i) - B_{inc}(E_i)}\right)\frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

$$\sigma(E_i) \simeq \frac{1}{\rho dx}\left(\frac{N_{int}(E_i) \times C_{int}(E_i)}{N_{inc}(E_i) \times C_{inc}(E_i)}\right)\frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

Beam Background Correction and Uncertainties

$$\sigma(E_i) \simeq \frac{1}{\rho dx}\left(\frac{N_{int}(E_i) \times C_{int}(E_i)}{N_{inc}(E_i) \times C_{inc}(E_i)}\right)\frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$



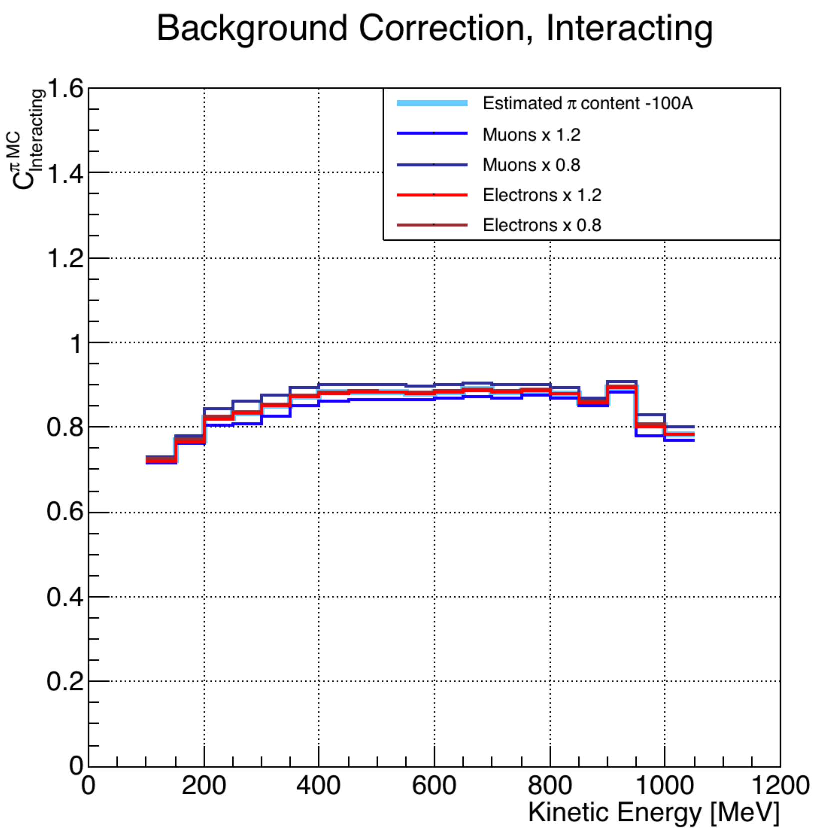
- Average beam composition after analysis selection cuts and thin-slice technique

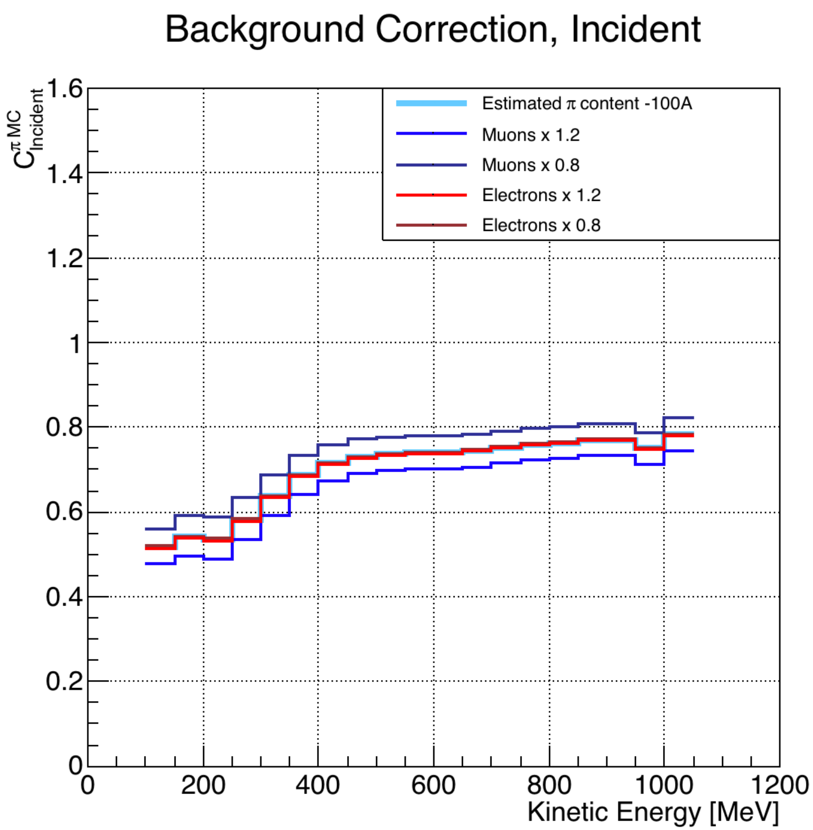
	Low Energy Beam Tune	High Energy Beam Tune
Pions	70.9%	82.3%
Muons	14.6%	13.5%
Electrons	14.5%	4.2%

- Uncertainties in the background content (assume uncorrelated)
  - Apply ±20% variation to muon content
  - Apply ±20% variation to electron content

Beam Background Correction and Uncertainties

$$\sigma(E_i) \simeq \frac{1}{\rho dx}\left(\frac{N_{int}(E_i) \times C_{int}(E_i)}{N_{inc}(E_i) \times C_{inc}(E_i)}\right)\frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

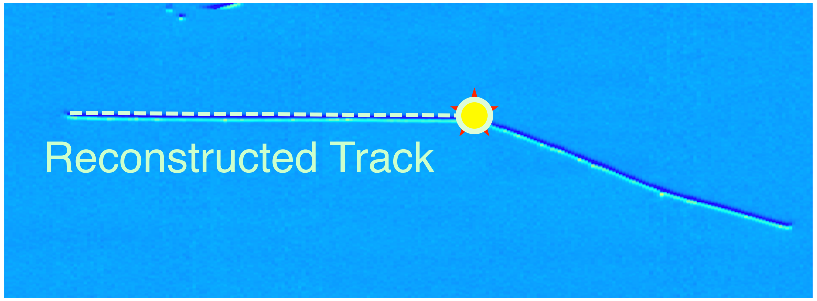




Reconstruction Efficiency Correction

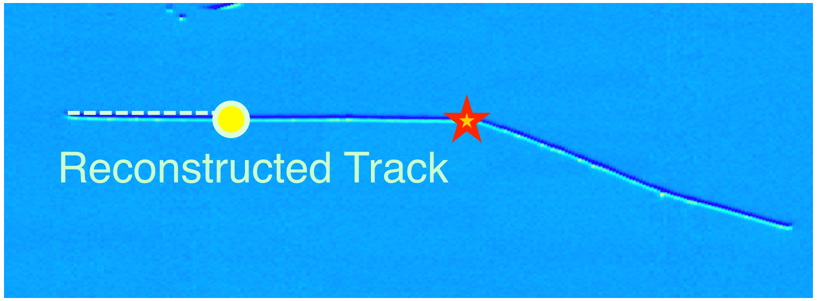
$$\sigma(E_i) \simeq \frac{1}{\rho dx} \left(\frac{N_{int}(E_i) \times C_{int}(E_i)}{N_{inc}(E_i) \times C_{inc}(E_i)} \right) \frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

Correct interaction ID



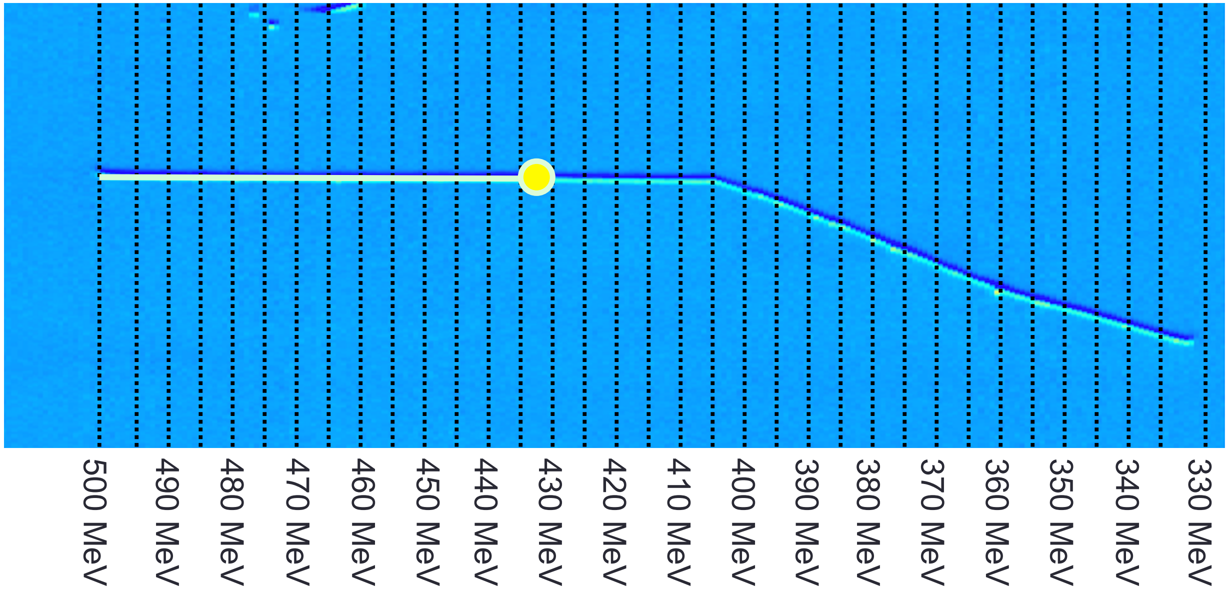
Missed interaction

Early stop



No sensitivity to scattering angles < 5°

Each slice is an independent experiment

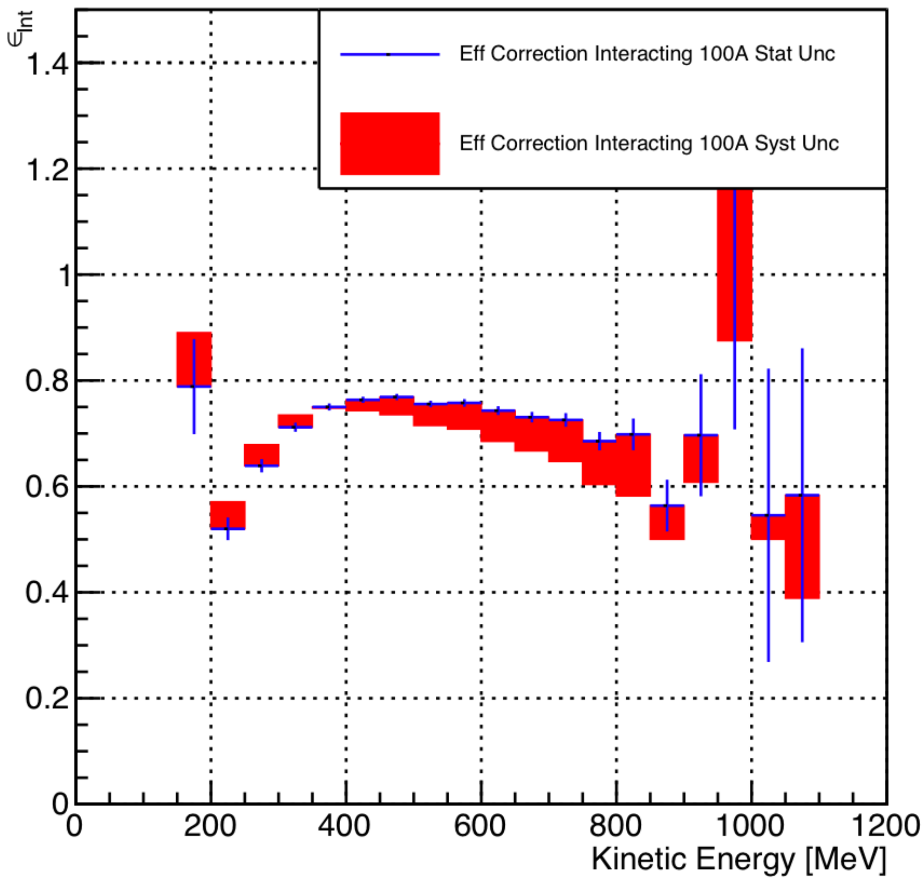


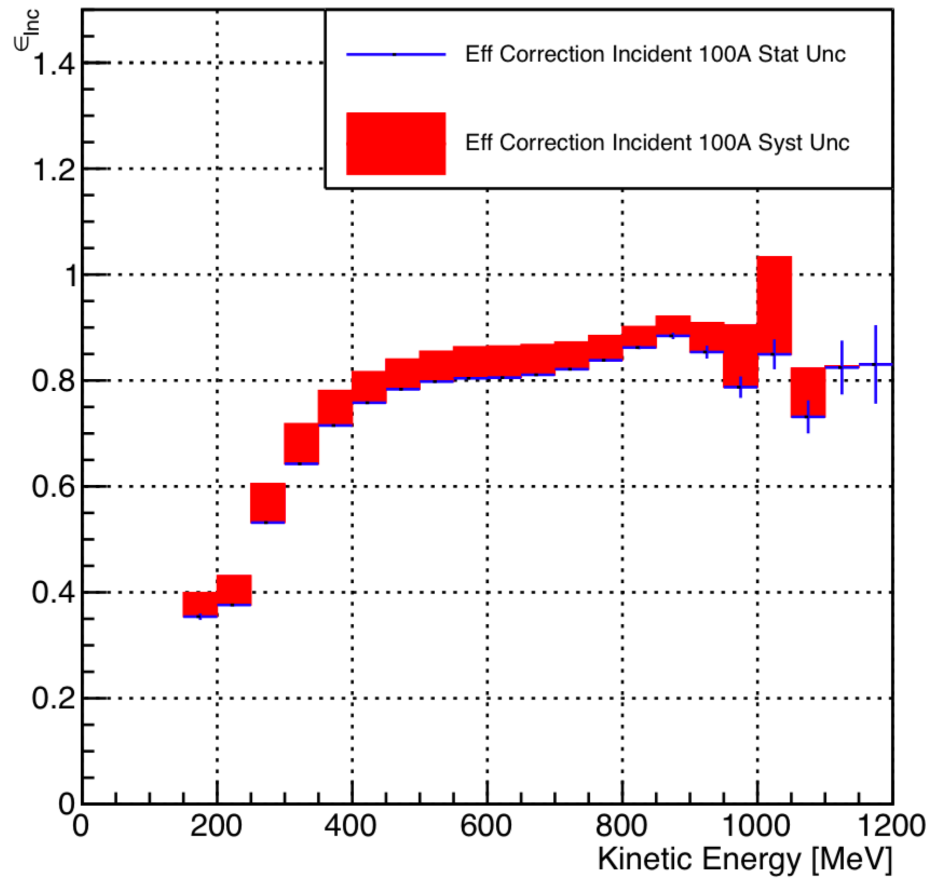
- Calorimetry does a good job of measuring the energy at each slice along the path of the particle, so we usually don't put things in the wrong KE bin
- BUT, if the reconstruction identifies an interaction too early or too late, we make a mistake in both the interacting and the incident histograms:
  - If interaction is found too early (reco track shorter than true track)
    - Too few entries in "incident" histogram, possibly affecting multiple KE bins
    - The 1 entry that goes into the "interacting" histogram may be in wrong KE bin
  - If interaction is missed/found too late (reco track longer than true track)
    - Too many entries in the "incident" histogram, possibly affecting multiple KE bins
    - The 1 entry that goes into the "interacting" histogram may be in wrong KE bin

Reconstruction Correction Efficiency

$$\sigma(E_i) \simeq \frac{1}{\rho dx}\left(\frac{N_{int}(E_i)\times C_{int}(E_i)}{N_{inc}(E_i)\times C_{inc}(E_i)}\right)\frac{\epsilon_{inc}(E_i)}{\epsilon_{int}(E_i)}$$

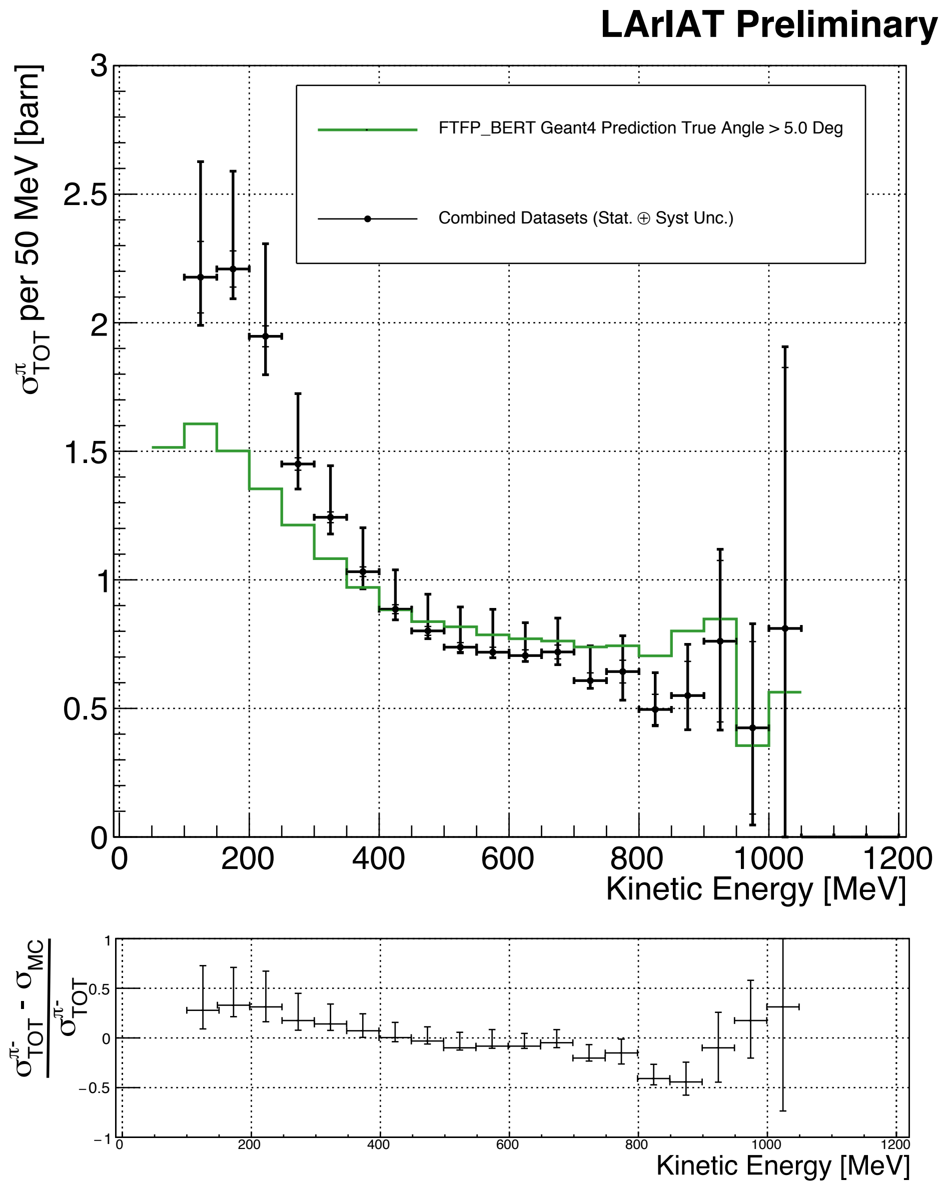
$$\epsilon_{inc}(E_i) = \frac{N^{\mathrm{RECO}}_{inc}(E_i)}{N^{\mathrm{TRUE}}_{inc}(E_i)}$$





Cross section after corrections

- After applying the corrections for background and efficiency to combined data from the low-energy and high-energy beamline tunes, cross section is compared with Geant4 prediction
- Discrepancy at low energy is still under investigation
  - Part of this difference could be due to a not-yet-identified systematic
  - But, since the resonance region is the hardest to model (and G4 model for argon is interpolated from data on heavier/lighter nuclei), difference may also be pointing to a model deficiency

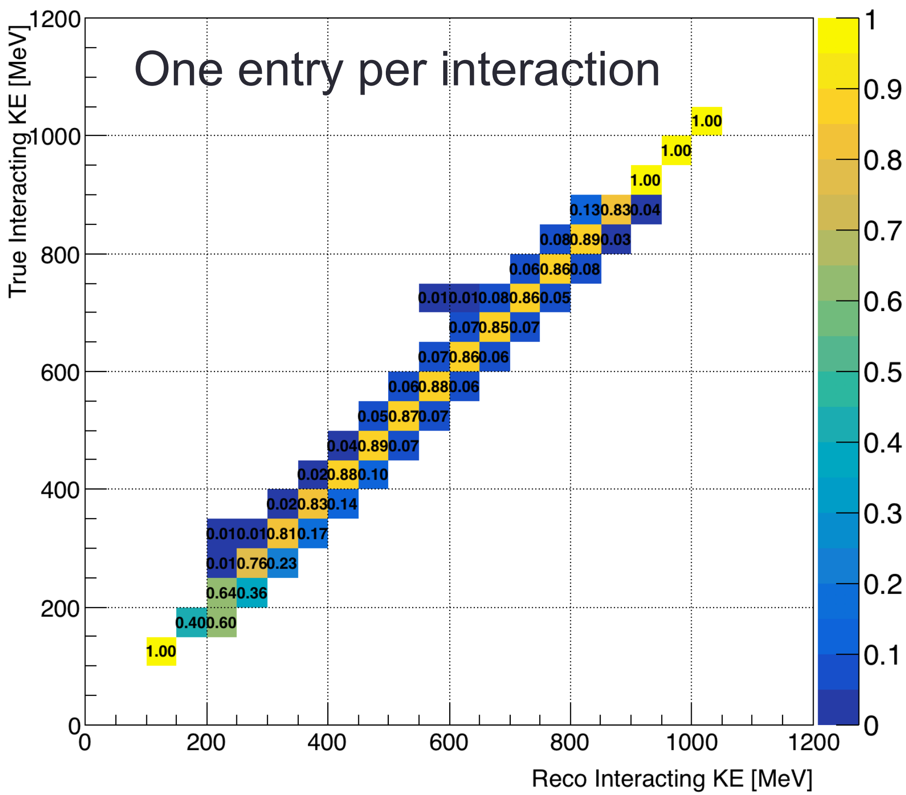


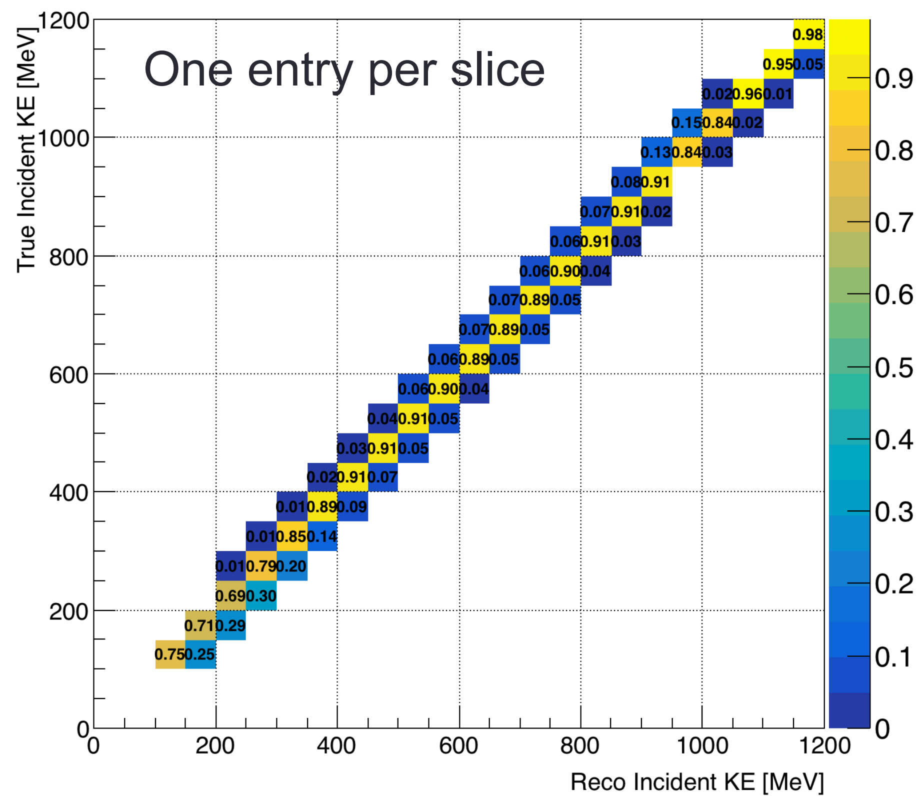
Summary

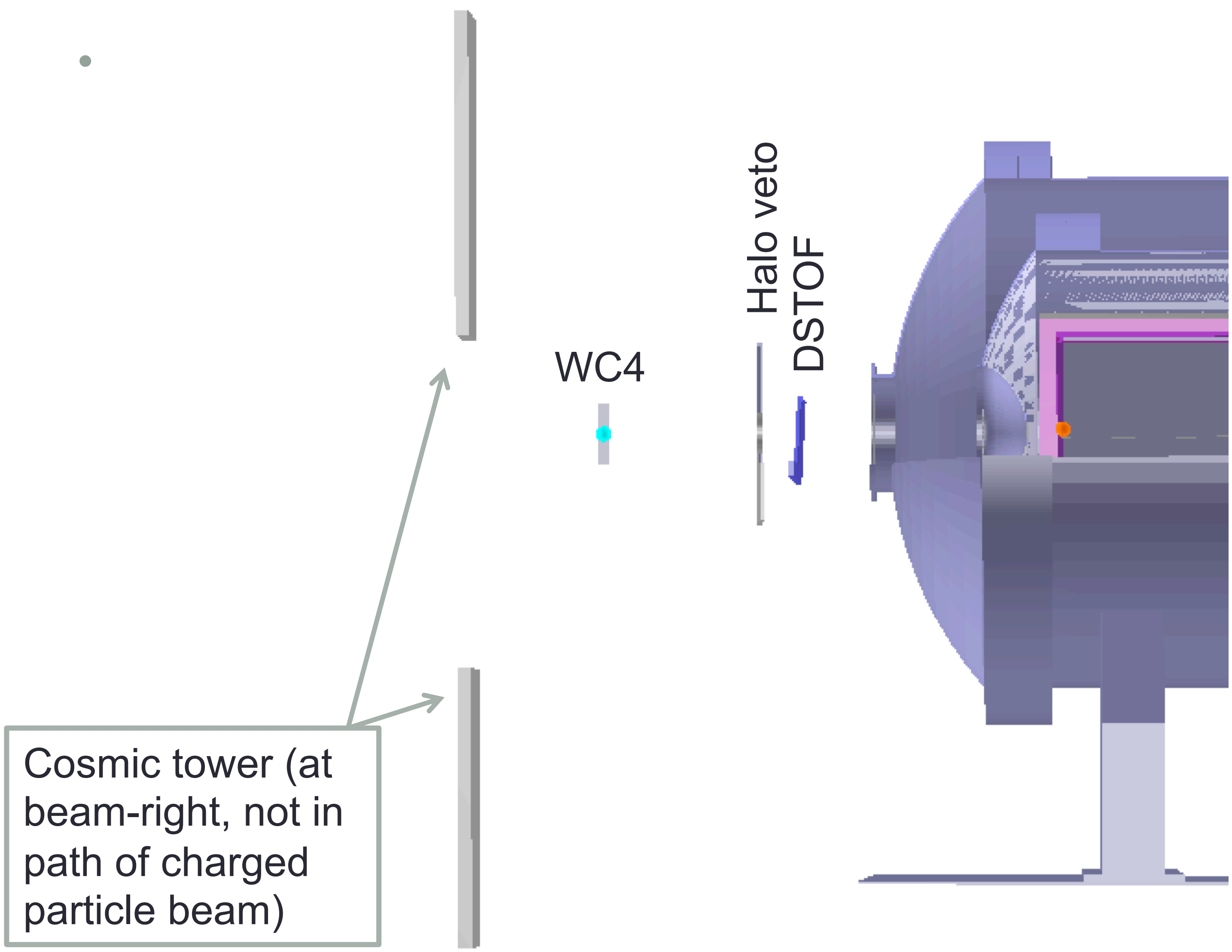
- Thin-slice method for measuring the cross section
  - Treats each slice of the TPC as an independent yes/no experiment
  - Care must be taken in subtracting background and correcting for reconstruction inefficiencies
- Most important uncertainties to consider:
  - Background subtraction: how well do you know the BGs?
    - LArIAT's downstream muon range stack *should* have been useful to help constrain the background, but some hardware issues have prevented us from using this information so far
  - Energy bias/uncertainty
    - How much energy to account for due to particles traveling through uninstrumented materials. Small changes in angle result in not insignificant changes to energy loss
    - Accurate beamline momentum measurement is critical to cross section measurement

Extra Slides

Energy reconstruction






WC4
Halo veto
DSTOF
Cosmic tower (at beam-right, not in path of charged particle beam)